Lessons learned from Nepal Earthquake from damages observed in buildings with low-strength masonry and non-ductile RC construction

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ABSTRACT

The devastating Gorkha (Nepal) Earthquake of April 25 of 2015 and aftershocks caused wide spread damages and collapse of residential houses, school buildings and health clinics in hilly regions of central Nepal. More than 750 thousand houses including more than 7000 school buildings were either severally damaged or collapsed requiring reconstruction. The limited number of strong motion records showed that shaking intensity was not high and the significant frequency of the ground motions was out of the range of most of the buildings. Still the wide spread damages and destruction of houses, particularly of those built with stone and brick masonry as well as of those non-ductile reinforced concrete buildings offers insight to the major causes and mechanics of damage from moderate to low shaking ground motions.

This paper presents general damage patterns to different housing typologies: rural stone masonry, adobe construction with timber flooring, unreinforced clay brick masonry and reinforced concrete buildings of less than 5-story high based on field observation made after the earthquake. It also provides a critical analysis of typical cases of damages and collapse in each category and draws lessons that are applicable to more general situation of earthquake exposure of vulnerable built-environment due to presence of unreinforced masonry and non-ductile reinforced concrete buildings. The characteristics of ground motion and its impact to the type of damages will also be discussed. As the earthquake showed the effectiveness of simple, yet cost friendly, seismic upgrades in selected school buildings in Nepal, the paper highlights lessons learned to that effect, too. A brief account of the reconstruction which is currently carried out aiming to phase out by the end of 2020 is also made, particularly in the aspect of how these lessons are incorporated.

Keywords: Earthquake damage, Lesson learned, Unreinforced masonry, Non-ductile RC, Seismic upgrading

INTRODUCTION

On April 25, 2015, Nepal was hit by an earthquake with a moment magnitude (Mw) of 7.8. The epicentre was located in Gorkha, which is about 80 km northwest of Kathmandu, the capital of Nepal. The main event was followed by several large aftershocks including a severe one on May 12, 2015, with magnitude Mw of 7.2 and epicentre located at Dolakha, about 100 km northeast of Kathmandu. The fault rupture was about 40km wide and stretched from Gorkha to Dolakha in the east west. From the instrument recordings in Kathmandu, it was observed that the city experienced mostly long-period shaking with peak ground acceleration (PGA) of about 0.16 g, and high ground displacements (maximum values of about 80 cm). The earthquake caused 9,256 deaths and another 22,300 people were injured in Nepal. About 850,000 houses were damaged by the earthquake. Overall, 2,649 public buildings and 510,762 private dwellings collapsed, while 3,617 public buildings and 291,707 private dwellings suffered partial damage. More than 7,000 school buildings and 1,085 healthcare facilities suffered damage [1, 2]. The earthquake also affected approximately 2,900 structures with cultural and heritage values. Building typologies that were most severely impacted by the earthquake were low-rise unreinforced masonry buildings, including adobe buildings and rural stone masonry buildings constructed using mud mortar. Most affected areas were remote rural areas with stone masonry dwellings that were either severely damaged or collapsed due to the earthquake. Reinforced concrete buildings with unreinforced masonry infills also collapsed in Kathmandu and other urban areas. Out of all the buildings damaged in the earthquake, 79% were masonry wall based buildings including that from stone, sun dried brick or burnt clay [3]. Some of the reinforced concrete buildings with unreinforced masonry infills were also damaged in Kathmandu and other towns in hilly regions.

There was limited information on the characteristics of ground motion in the damaged are as only few strong motions recordings were available in the valley. From those recordings, it was observed that Katmandu (see Figure 1) experienced mostly long-period shaking (0.16g PGA and peak ground displacements of about 80 cm). The concentration of damage in Kathmandu to adobe houses with flexible floors, old buildings and only to poorly built reinforced concrete building, as well as some damages to high rise buildings, clearly shows the effects of long period motion (at periods centered around 4.5s). In contrast, for short-period buildings, where most of the residential and commercial buildings lie around, low spectral accelerations were obtained.

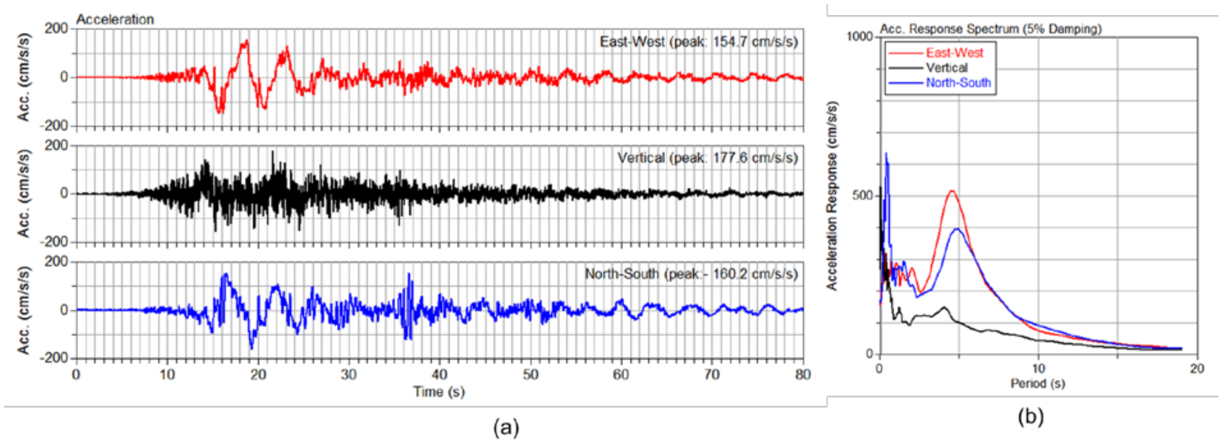


Figure 1. Ground motion recorded at Kantipur station, Kathmandu: (a) time history, (b) response spectra (5% damping).

Nepal is situated in high seismic region where Indian tectonic plate which subducts under the Tibetan plate. Historical records show that major earthquakes occur in and around the country every 70-100 years, the last big one prior to the 2015 event was in 1934 that killed over 8000 people in Kathmandu [4]. Based on historic records and other measurements, a big earthquake was expected that would cause significant damage to the vulnerable buildings and infrastructures [5]. It was estimated that an earthquake of similar shaking intensity of the 1934 event would have completely destroyed 20% of Kathmandu's building stock and would have heavily damaged another 40 percent in a scenario case [4]. While the shaking intensity of 2015 earthquake was relatively small as recorded in Kathmandu (PGA~0.16g), collapse and heavy damage was observed not only to low strength masonry houses but to some reinforced concrete buildings in Kathmandu and other towns. The large stock of building with low strength masonry with no seismic resisting elements in the earthquake hit area is the main factor for the loss. Table 1 shows the prevalent of low strength masonry houses, built primarily with random rubble units in mud mortar, in the region. The data shows that about 80% of houses were made of masonry units without reinforcements.

Table 1: Existing building typology in the highly affected districts

(Source: Central Bureau of statistics, Nepal, 2011)

Low strength masonry	**Cement based masonry**	**Reinforced concrete frame with infill**	**Others (wood/ bamboo based)**
58%	21%	15%	6%

The initial damage assessment as shown in Table 2 illustrates that almost 98% of the total collapsed buildings fall under this category [3]. Even buildings with standard construction material, like reinforced concrete, suffered damages under low shaking ground motions as they were designed and built poorly with very little or no seismic considerations. About 2% of the completely collapsed buildings fall under this category.

Table 2: Damages in building categories in the 2015 Gorkha Earthquake

Building types	**Fully collapsed**	**Partially damaged**
Low strength masonry	474,025 (95%)	173,867 (67%)
Cement based masonry	18,214(3.7%)	65,859 (25.6%)
Reinforced concrete frame	6,613 (1.7%)	16,971 (6.7%)

Nepal developed its first National Building Code (NBC) in 1994, and included seismic loading and earthquake resistant design provisions [6]. The code, however came into legal effect only in 2006 when a law was passed to require city government to follow it. However, the enforcement of the building code was not effective throughout the country.

Field surveys of the earthquake damage were carried out in the earthquake aftermath, both in rural and urban centres. Field surveys were also carried out during the period of reconstruction that started almost a year later. The lessons learned from analysis of both surveys of damage and reconstruction of houses are discussed in the paper.

DAMAGE TO LOW STRENGTH MASONRY

Houses made of stone masonry walls

Stone masonry houses suffered most of the collapses and heavy damage throughout the earthquake affected central hill of the country. These houses are typically regular in plan and one- to three-storeys high with floor height of about 2.4 m. Most houses have 50 to 60 cm thick stone walls with mud mortar, with interior and exterior stone masonry wythes separated by a layer of mud mixed smaller pebbles. The floors have wooden joists that run parallel to the building width and are covered either by wooden planks or bamboo mats that run across the joists supporting clay toppings. Most buildings have pitched roofs, which are made of wooden purlins and rafters. Mostly the roofing material is lightweight thatch or CGI sheet, heavy stone states are also used in some cases.

A typical damages observed in the stone masonry buildings were partial or complete out-of-plane collapse of walls, including gable walls; diagonal cracking in the piers between the openings; vertical cracks at the wall corners and collapse of upper storeys in the two- or three-storey houses. It was observed that some stone masonry buildings that have wooden bands provided at the lintel level survived the earthquake. Figure 2 shows two examples cases of stone masonry from earthquake hard-hit area. The first house (Figure 2a), which did not have band or any sort of anchoring of roof or floor to walls, collapsed completely. The other one (Figure 2b) had continuous timber band at floor levels and roof system was anchored with front walls. Despite being close to epicenter of the major aftershock of 12th May, 2015, it was undamaged.

(a) (b)

Figure 2. Damage to stone masonry houses: (a) complete collapse in typical house, (b) no major damage in the house with horizontal timber bands

Delamination was widely observed in think multi-wythe stone masonry walls where small stones were used in walling with no thru stones. These damages were seen in case of typical partial out-of-plane failure of gable or side walls. Complete out-of-plane-failure that led to collapse of houses were widespread throughout the earthquake hit area. These damages were prevalent when lintel or floor bands were absent and floor joists were not tied to supporting walls. Figure 3 shows delamination of wall in a partially collapsed wall and complete out-of-plane failure of a side walls in another house. Observed poor performance of these side walls is due to the fact that the timber floor and roof system that consist of joists are typically supported on, and sometime anchored with, longitudinal walls but side walls have limited connection only through planks with small bearings. In some buildings, only gable walls got collapsed in out-of-plane. These gable walls were made with same heavy stone material and were freely standing with no anchorage with roof and floor.

Separation of orthogonal walls in the corner region was also widely observed in partially damaged buildings. Figure 4 shows close-up looks of wall separations taken from two separate damaged houses. In buildings with lintel or floor bands, it was evident that those bands intercepted those separation cracks and minimized the damages.

(a) (b)

Figure 3. Out-of-plane failure of walls in stone masonry houses: (a) delamination, (b) complete failure of walls

Figure 4. Separation of walls in corners where horizontal bands were absent

Collapse of the floor due of insufficient bearing of the floor joists on the support walls was observed in several houses during the survey. It was also observed that buildings did better when joists were extended to create balcony, typically in second floor. This might be due the fact that joist helps to confine the wall and act integrally. In-plane inclined crack were also observed in stone masonry walls but they were mostly limited to extended cracks from corner of openings. Similarly, stone masonry houses that have rigid concrete slab performed well except in some schools where walls were too heavy that load was excessive for unreinforced walls to resist and school buildings collapsed.

Unreinforced Brick Masonry buildings

The building stock of masonry buildings with brick units was small in the earthquake hit area compared to stone masonry houses. Extensive damage was limited to brick masonry with mud mortar. For cases were the walls have two wythes of brick-outer wythe made up of burned brick and inner wythe from sun dried bricks get delamination. Other damages patterns were similar to stone masonry. The cause factors for the damage were also similar. However, diagonal cracks in walls were more prevalent in brick masonry houses (Figure 5).

DAMAGE TO REINFORCED CONCRETE BUILDINGS

Reinforced concrete frame construction has been the main construction type for residential houses and commercial buildings in Kathmandu and other urban centers in Nepal since early 1990s. Most of them are low-rise with 3-5 story high. Due to the lack of proper building code compliance and poor quality of construction, the majority of these buildings have high seismic vulnerabilities owing to one or more irregularities, non-ductile construction, and lack of lateral load resisting mechanism.

The proportion of the damage per building typologies in the Gorkha earthquake shows that this building stock did not suffer collapse or damage compared to masonry buildings (Table 2). This is obviously attributed to better performance of concrete material than that of low strength masonry. However, it is noteworthy that the typical period range of these buildings is not close to the predominant period of the earthquake, 4-5 sec. The recorded motion in Kathmandu shows that the peak ground acceleration is 0.16g and spectral acceleration around the period of interest is about only 0.2g. Well built reinforced concrete construction is not expected to suffer any damage to this shaking. This also implies that the damages observed in some buildings of this typology indicate several problems in the design and construction.

Figure 5. Diagonal in-plane shear cracks in brick masonry walls

The earthquake-induced structural damage in low-rise RC construction is mainly attributed to inadequate detailing of RC structural components and poor construction quality, increased seismic demand due to structural irregularities, and shear or flexural failure of RC frames with infills [7]. Figures 6a, 6b and 6c show typical damages observed in RC buildings when they have one or more those deficiencies. In figure 6a, column tie reinforcements with 7mm diameter bar were spaced at 250mm and have with 90º hooks. The concrete in column might not get the confinement needed for the required resistance. The size of columns is 300mm x 300mm, but the beams are larger with 300mm width and almost 6000 depth resulting into stronger beams than columns. Figure 6b represents typical ground storey failure due to soft story generated from large openings or open front retail stores or restaurants. The problem was severe in major shopping streets passing through town-centres as buildings have more open first stories. In hill towns, the problem was aggravated as they have buildings in shopping districts in hill ridge requiring unequal columns to offset the ground level difference. Damage was also observed in infill walls in RC buildings. Figure 6c shows an example how the RC frame buildings with infill acts dominantly in shear mode due the presence of infill. Although RC frame construction were supposed to respond in flexure ideally, these building resisted the ground shaking with significant participation from the walls. Once shear demands exceed the capacity of the masonry walls severe damage occured to these buildings, sometimes leading to collapse.

(a) (b) (c)

Figure 6. Damage in reinforced concrete buildings with brick infill walls: (a) poor detailing of rebars in concrete column, (b) soft-storey collapse of buildings due to open first floor , (c) damage to infill walls and concrete column due to shear

PERFORMANCE OF RETROFITTED MASONRY SCHOOL BUILDINGS

School buildings were hardest hit by the earthquake throughout the central and western hilly regions of Nepal. A total of 8,242 public schools were damaged in the earthquake with estimated losses of US$313 million in the education sector alone [2]. A study conducted by National Society for Earthquake Technology-Nepal (NSET) in early 2000 [8] reported that public schools buildings were significantly vulnerable to any seismic event. Following the initiative of NSET in seismic upgrading of 40 schools throughout the country, the Government of Nepal started a major project to retrofit about another 250 school buildings in the Kathmandu valley in 2012. A simple jacketing of unreinforced masonry walls with reinforcing steel mesh was the primary method of upgrading these schools. It was observed that all schools retrofitted in Kathmandu by the government or NSET performed well in the earthquake with no noticeable damages. Those simple method were proved effective enough to protect those low strength masonry school buildings from the earthquake [9].

HOUSING RECONSTRUCTION

Progress in Housing Construction

It took almost a year for the government to establish guidelines for an inspection system combined with provisions of housing grants for more than 700 thousands homes to be reconstructed in the earthquake affected area. The Government of Nepal (GoN) issued first a design catalogue that included templates for design of simple rural houses targeting the post-earthquake reconstruction after 6 months of the earthquake. During the first year, the government and other development agencies focused in capacity building by training of engineers, technicians and masons needed for the reconstruction. It took more than a year to set up a housing grant system combined with inspection mechanism to ensure that newly built homes were in compliance with the developed guidelines. However by that time, almost 20,000 houses have been already built by homeowners themselves.

Under the housing grant system, the government facilitated reconstruction of private houses with a grant of USD 3,000 for each household. This grant was disbursed in three installments, subjected to inspection by engineer for earthquake resistant compliance. Figure 7 shows three milestones of construction stages associated with the grant installments [10].

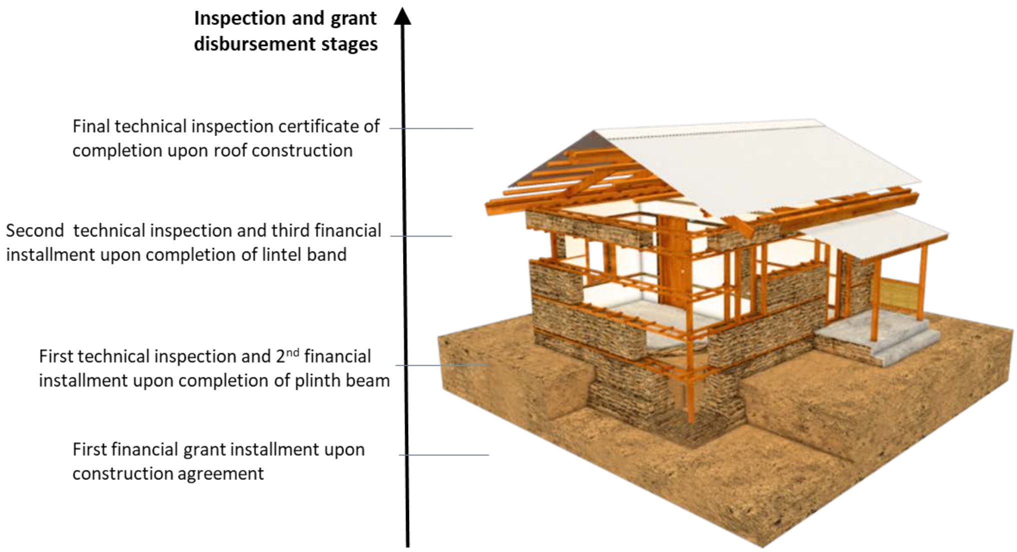


Figure 7. Schematic illustration of reconstruction inspection stages of rural houses supported by the government grant system

The inspection guidelines include a check sheet that a field engineer appointed by the government should verify at the three stages of construction- at plinth level, at lintel level and upon completion. It was found that a very few houses passed (less than 5%) the first and second inspections, even after the second anniversary of the earthquake in 2017. To address the problem, the government increased the technical support and issued a correction manual to help household to fix the deficiencies and proceed with the rest of the construction. Figure 8 shows the progress of housing reconstruction since early 2017. It illustrates significant progress in the fourth quarter of 2017, when additional support had been provided to the communities.

Provision of Earthquake Resisting System in Construction Guidelines

There were several lessons to be learned from the damage to rural houses, as well as, reinforced concrete construction in urban centres. One of the significant lessons related to construction of low strength masonry is that they need some form of reinforcement and confinement to provide integrity to the structures. While full detailed distributed reinforcement throughout may not be practical considering resource constraints, selective reinforcement using timber, bamboo, and steel bar or wire mesh is warranted to protect these houses from crumbling in a future earthquake event. Accordingly, the focus of the reconstruction technical guidelines for rural construction has been in two fronts: (a) configuration restriction, (b) provision of reinforcement.

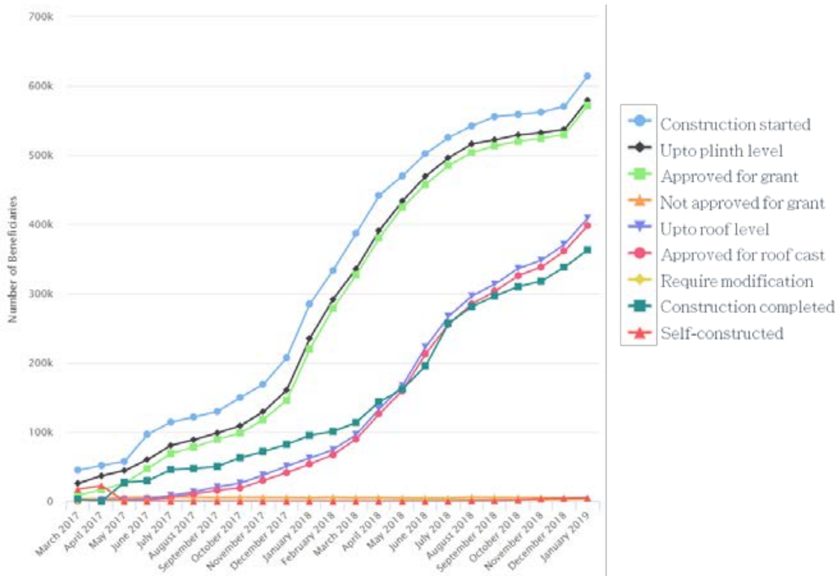
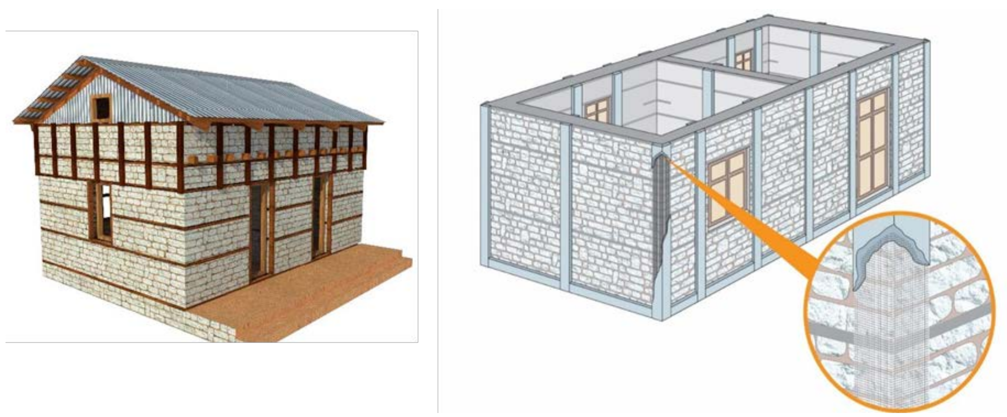


Figure 8. Progress status of post-earthquake housing reconstruction up to January 2019 (Data source: Ministry of Urban Development and Housing, Government of Nepal)

Figure 9 shows typical reinforcement provisions in the government guidelines for construction of stone masonry houses. Confinement of wall corners by external reinforcement mesh and integrity of system to be ensured by horizontal bands at sill level, lintel level and floor levels are major improvement in low strength masonry houses. Similarly the guidelines include provisions to ensure that roof and floor systems are structurally connected to supporting walls, gable walls are made of light material, and orthogonal walls are connected intermittently through reinforcing elements. The technology looks simple and may give impression that it does only little to protect the building. However, most of the damages in the earthquake were attributed to the lack of the same in conventional construction.



(a) (b)

Figure 9. Vertical and horizontal reinforcement provisions for stone masonry houses: (a) using timber as the reinforcing elements (b) use of wire mesh as the reinforcement

The existing building code for reinforced concrete design has been used for the reconstruction of houses in urban areas. However, the existing seismic code and its loading provisions have not been updated for a long time. Although a process to update the code was started in 2017, there is still progress to be made. This has implication to the housing reconstruction in Kathmandu and other urban centers. A provisional measure has been implemented using an updated pre-engineered design template for reinforced concrete design for houses up to 3 storeys high and with a simple regular plan shape.

LESSON LEARNED FROM THE EARTHQUAKE AND RECONSTRUCTION

Some important lessons can be derived from ground motion characteristics, damage of low strength masonry houses and low-rise reinforced construction, good performance of simple seismic upgrading of masonry schools buildings, as well as, from the process and progress of reconstruction.

While the recorded ground motion observed in Kathmandu was about only one-third of design acceleration in the NBC, still several reinforced concrete buildings collapsed or were heavily damaged owing to significant seismic deficiencies. Although many poorly built buildings survived this earthquake, it should be recognized that these could be subjected to severe damage and collapse in a future earthquake of similar magnitude but with different ground motion characteristics. Kathmandu city did not have high rise buildings that would have a fundamental period close of predominant period of this earthquake, but the rapid growth of high rise buildings in the city may result in a different scenario during future earthquakes of similar characteristics.

Stone masonry is a prevalent type of rural housing construction in the hilly regions of Nepal. As stone is the most accessible material for local communities and they may not be able to afford alternative materials, design and construction guidelines should address the inherent deficiencies of the system employing minimum reinforcement using timber, bamboo, wire mesh or steel bars. The integrity of walls and connection between wall and floors need to be ensured. Some low-rise reinforced concrete buildings suffered major damage even in areas of low intensity shaking due to major seismic deficiencies in regularity, detailing of reinforcements and disregards of infill walls. Next update in the building code should address these issues in addition to update in seismic loading itself. It was learned from the earthquake that even simple seismic upgrading of low strength masonry building with jacketing can be effective. Many adobe and other brick school buildings were saved in earthquake due to the upgrading. Since the shaking was high enough in the last earthquake, more research is needed to test their effectiveness in higher shaking.

The reconstruction of houses did not achieve momentum for two years as the country did not have a reconstruction plan in place for such major earthquake, although the country was known to be in high seismic hazard region. The first two years after the earthquake were spent on establishing a system for reconstruction, developing guidelines and training engineers, technicians and skilled worker needed for the construction. An important lesson that was learned is that these measures could have been developed and implemented during pre-disaster time using effective planning tools and risk-reduction measures. That would avoid the hardship those affected households endured in past monsoons and winter seasons. This lesson equally applies to any communities that are located in seismic hazard zones.

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